Sediment Sampling and Analysis for Stream Restoration Projects

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Complexity	Value	Cost
Low Moderate High	Low Moderate High	Low Moderate High

OVERVIEW

Sedimentation processes, including erosion, transport, deposition, and consolidation and sorting, are critical considerations in evaluating stream stability and developing restoration designs. The form of a channel is a consequence of the magnitude, timing, and frequency of both the runoff and the sediment yield from the watershed. Sediments on the bed of the channel and the soils in the banks also play a role in defining channel form, as they establish the channel's resistance characteristics and thresholds for erosion and degradation.

Most sediments transported by streams ultimately (or periodically) deposit in the channel or floodplains, creating new habitats critical to the ecological health of most streams and riparian systems. These sediments, particularly the silt and clay fractions, are often accompanied by associated nutrients and contaminants – important to the chemical condition of the stream system and its associated biota. Sediments on the streambed are home to a wide array of invertebrates such as insects and mussels, provide spawning substrate for many aquatic species, and are important habitats for early life stages of many fishes.

The challenges posed by assessment, remediation, and management of sediment in the United States are not trivial. According to the U.S. Environmental Protection Agency (1998), 10 percent of the sediment underlying U.S. waters contains chemicals at concentrations that may adversely affect fish and wildlife. More than 5,000 U.S. water bodies have been listed as impaired by "clean" sediments under Section 303(d) of the Clean Water Act, making sediments the leading pollutant. Watershed management plans and remedial actions may be required in these cases to manage sediments and reduce impacts, or to meet Total Maximum Daily Load (TMDL) standards.

Figure 1. Sediments define channel form, resistance, stability, and ecological character.

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This technical note outlines procedures for the sampling and analysis of sediments associated with typical restoration projects.

PLANNING CONSIDERATIONS

The scope of needed sediment investigations must be identified early in the planning stages for a project because the first phase of sediment investigations typically occurs before implementation, and can have a profound effect upon schedules and budgets. At a minimum, restoration projects require a qualitative analysis of sediment processes and quantification of the size distribution of the sediments on the bed of the stream. This can usually be accomplished during a preliminary site investigation, and involves less than a man-day of effort.

At the other end of the spectrum, sediment studies may involve detailed sampling and analysis to formulate sediment rating curves for long-term numerical simulations and, in rare cases, physical modeling of particularly complex phenomena may be needed. These efforts can span two or more years and involve significant expenditures.

The aim of sediment investigations is to develop a sufficient understanding of the sediment processes within the system to assess the existing and future conditions with and without remedial measures. What constitutes “sufficient” depends upon the risks and consequences, as well as the character of the stream system and the nature of the remedial action.

The nature of the impairment is often unknown when the problem is discovered. Sediment investigations for impairments that are localized must be treated differently than those that are systemic. Thus, it is often necessary to assess the channel and watershed to identify geomorphic conditions and trends related to the important sediment characteristics and processes as the first step in a restoration effort. Understanding and treating systemic causes, in conjunction with local treatments, will maximize both short- and long-term project effectiveness.

The studies necessary to complete the restoration project depend upon the findings of the initial geomorphic investigations — so a staged approach to sediment investigations is usually recommended. The staged approach emphasizes simple, quick, often qualitative analyses that are used to screen problems. At times the initial investigation will indicate a need for further study or the remedial action is a new procedure that must be evaluated to understand its effects, eliminate concerns, and determine the need for improvements. In these cases, more complex, expensive, and time-consuming studies and analyses are implemented.

The studies used in sediment investigations can be generalized into those that support characterization of the sediments, those used to support system stability analyses, and those used to support local stability analyses. Table 1 summarizes the most common sediment investigations, their use, and the frequency and circumstances under which they are applied.

This technical note presents an overview of the techniques most frequently employed in assessing sediment characteristics, system stability, and reach stability for restoration projects. Other techniques that are occasionally employed are summarized in the last section of the technical note.

SEDIMENT CHARACTERIZATION

Sediment characteristics that may be important in executing stream restoration projects include the sediment size, shape, specific weight, fall velocity, and parent geology. It is also sometimes important to quantify constituents such as pollutants and organic material that may be associated with sediments. Determining the median size and size distribution of the sediments is necessary for most projects, while the other characteristics are important only when warranted because of unique project circumstances.

Table 1. Summary of common sediment investigation techniques.

Category / Technique	Use	Frequency/Limitations
Sediment Characterization		
Wolman Pebble Counts	To determine the size distribution of surface sediments within the channel. Used to assess stability and habitat, and for resistance computation.	Almost always used for projects having substrate coarser than sands. Not recommended for systems with predominantly sand or finer sediments.
Sieve Analyses	To determine size distribution of sediments in bed, banks, or water column. Used for stability, transport, habitat, and scour analyses, resistance estimates, and structure design.	Frequently employed, but limited to sediments smaller than cobbles, unless other techniques are also employed.
Embeddedness Computations	To characterize the degree to which fine sediments fill the interstices of coarse sediments on the streambed. Used primarily to evaluate habitat.	Often employed, although the verity and accuracy of existing techniques is questionable. Limited to gravel or larger materials on the bed surface.
Quality Analyses	To determine the presence or concentration of contaminants, organic matter, or other constituents associated with fine sediments.	Infrequent. Only indicated when contaminated sediments presence is likely or to measure organic material. Used for cohesive sediments only.
System Stability		
Sediment Yield	To determine the source, load, and composition of sediments contributed to a system from overland flow, slides, tributaries, and bed and bank erosion.	Frequently used, particularly for projects in which sediment deposition in the active channel is likely, or where reservoirs or lakes are present.
Bank Erosion Assessments	To identify causal mechanisms for bank loss, to quantify recession rates, and to estimate the sediment yield.	Nearly always used as a means of assessing channel stability and to formulate restoration designs.
Bed Level Changes	To identify aggradation and degradation trends within the system.	Nearly always used as a means of assessing channel stability and to formulate restoration designs.
Sediment Load Sampling	To quantify the sediment concentration in the water column for a given discharge and to develop sediment rating curves for continuity analyses.	Seldom used. Requires extensive sampling spanning a wide range of flow conditions over several years– requiring significant time and funding.
Watershed Modeling	To quantify hydrologic and sediment yield characteristics of a watershed under a variety of conditions.	Sometimes used. Generally practical in situations where significant land use changes are anticipated.
Reach Stability		
Incipient Motion Analyses	To determine likelihood of the entrainment of sediment particles under given flow conditions.	Nearly always used, especially in gravel bed systems. Applicable mainly to systems with non-cohesive sediments.
Continuity Trend Analysis	To assess the transport capacity of a study reach relative to the immediate up- and downstream reaches.	Infrequently used, but is applicable to most projects. Counter indicated only when full continuity analyses needed.
Full Continuity Analyses	To assess long-term reach stability with respect to bed level changes.	Sometimes used. Warranted when long-term aggradation or degradation are expected and data are available.
Scour Analyses	To estimate the maximum anticipated scour depth associated with structures or debris within a system.	Nearly always applicable, but of limited use with cohesive sediments. Existing prediction methods have high uncertainty and often require model calibration and field comparison.
Sorting Analyses	To assess changes in the composition of the bed material and armor layer of sediments.	Seldom applied. Existing relations are complicated. Primary use is for habitat analyses when substrate is critical.

Sediment Groups

The above characteristics are often determined separately for different sediment sources, such as those within the water column, within the bed of the stream, in the streambanks and sometimes within the watershed. Thus, sediment sizes or gradations are often associated with the source or in situ location of the sediments, such as the bed material, the bank material, or the watershed sediments. For those sediments located within the water column under a given flow condition, several distinctions can be made.

The two most common means of partitioning transported sediments are into the categories of bed load and suspended load, or into the categories of bed material load and wash load. Each pairing, when summed, provides the total load (i.e. bed load + suspended load = total load; bed material load + wash load = total load), but the first approach divides the sediments on the basis of transport mechanism whereas the second makes the division on the basis of geomorphic significance.

Sediment Size

Investigating sedimentation problems such as scour, aggradation and degradation often requires a particle-size distribution of the bed material of the stream (Figure 2). Particle-size data are usually reported in terms of d_i, where i represents some percentile of the distribution, and d_i the particle size, usually expressed in millimeters, at which i percent of the total sample by weight is finer. For example, 84 percent of the total sample would be finer than the d_{84} particle size.

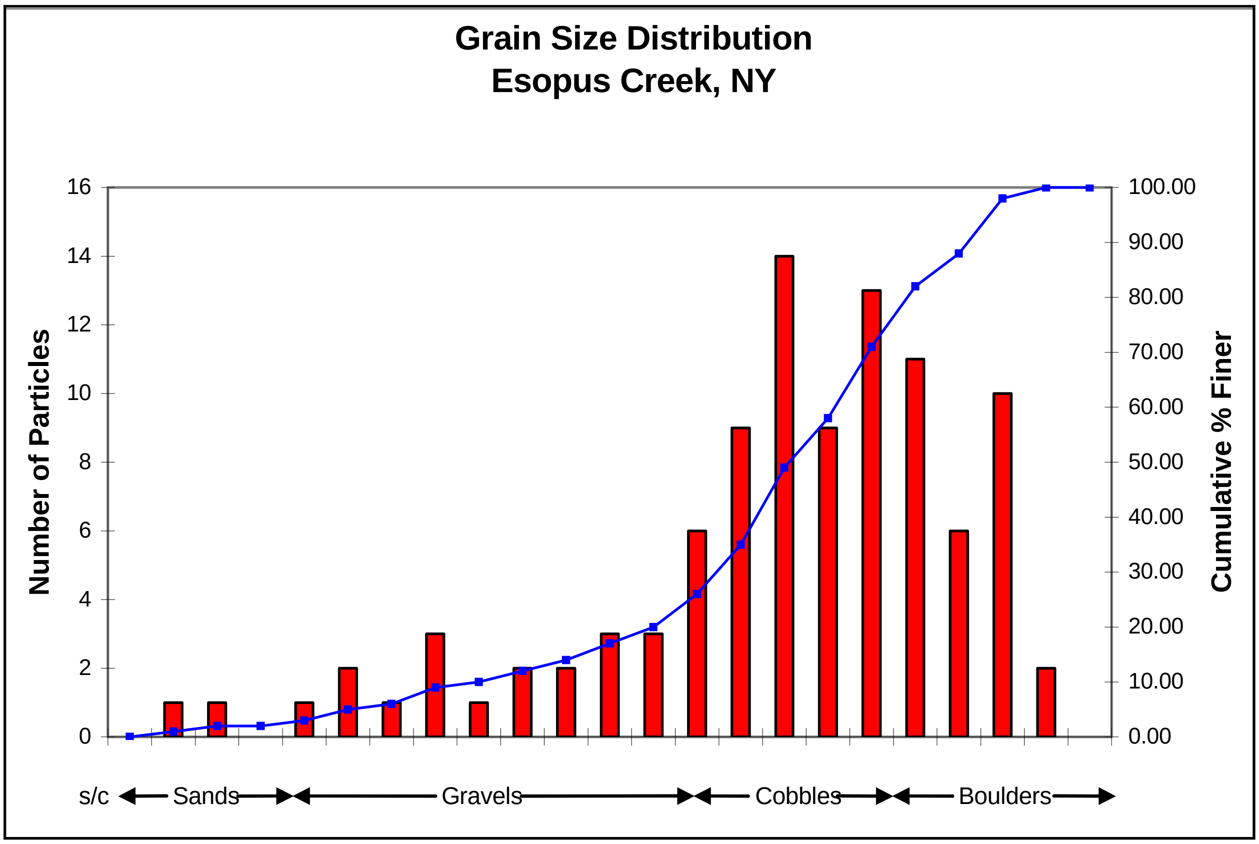

Figure 2. Sediment gradation curve (blue line) from a Wolman pebble count.

Sediments are often grouped into categories on the basis of their size, as reflected in Figure 2. Common size classes include boulders, cobbles, gravels and sands, as well as silts and clays. Each of these classes may be further subdivided according to size, as shown in Table 2.

The size of sediment particles can be measured by visual estimation, measurement using rulers or calipers, or with a set of sieves. With experience, practitioners can visually estimate grain size within sufficient accuracy for restoration analyses - at least down to silt sizes. For more refined analysis purposes, silts and clays (sediments finer than 0.0625 mm in diameter) should be analyzed by hydrometer analyses in a laboratory.

Sands, gravels, and smaller ranges of cobbles are measured directly or are assessed by sieving in the field or lab. Larger cobble sizes are evaluated by measuring individual particles, or through mechanical analyses using screens or grizzles.

Table 2. Sediment size scales and classes

Class name	d_s (in)	d_s (mm)	d_s (microns)	U.S. Sieve	Measure[1]
Boulder					
Very large	160-80	4000-2000			V, M, G
Large	80-40	2000-1000			V, M, G
Medium	40-20	1000-500			V, M, G
Small	20-10	500-250			V, M, G
Cobble					
Large	10-5	250-130			V, M, G
Small	5-2.5	130-64			V, M, G
Gravel					
Very coarse	2.5-1.3	64-32			V, M, G
Coarse	1.3-0.6	32-16			V, M, S
Medium	0.6-0.3	16-8			V, M, S
Fine	0.3-0.16	8-4		5	V, M, S
Very fine	0.16-0.08	4-2		10	V, M, S
Sands					
Very coarse	0.08-0.04	2-1	2000-1000	18	V, M, S
Coarse	0.04-0.02	1-0.5	1000-500	35	V, S
Medium	0.02-0.01	0.5-0.25	500-250	60	V, S
Fine		0.25-0.125	250-125	120	V, S
Very fine		0.125-0.062	125-62	230	V, S
Silts					
Coarse		0.062-0.031	62-31	400	S, H
Medium		0.031-0.016	31-16		H
Fine		0.016-0.008	16-8		H
Very Fine		0.008-0.004	8-4		H
Clays					
Coarse		0.004-0.002	4-2		H
Medium		0.002-0.001	2-1		H
Fine		0.001-0.0005	1-0.5		H
Very Fine		<0.0005	0.5-0.24		H

[1] V – Visual; M – Measure; G – Grizzle; S – Sieve; H - Hydrometer

Both graphic and statistical methods of data presentation have been developed for the interpretation of sediment size distribution data. However, most stream restoration analyses can be accomplished by determining the d_{90}, d_{84}, d_{50}, d_{16}, and d_{10} of the sediments. The median sediment size, d_{50}, is used for a number of analyses. The d_{90} or the d_{84} is often used for stability analyses, to estimate resistance, and in sediment transport formulae. The d_{16} is used to calculate distribution characteristics for the sediment mixture, and the d_{10} is often used to discriminate between bed material and wash load.

For a log-normal distribution, the geometric mean size of the sediments may be determined by the intersection of the cumulative frequency curve and the 50 percent exceedence line, or from:

$$d_{50} = \left(d_{16} * d_{84}\right)^{0.5} \quad (1)$$

The geometric standard deviation σ_g is:

$$\sigma_g = \left(d_{84} / d_{16}\right)^{0.5} \quad (2)$$

Other statistical measurements for sieved samples that are occasionally employed in stream restoration analyses consist of additional measures of central tendency (including median, and mode); a measure of the degree of scatter or sorting; kurtosis, the degree of peakedness; and skewness, the lop-sidedness of the curve. Various formulae have been defined for these parameters (Folk and Ward 1957).

Wolman Pebble Counts

In steep rivers with substrate much coarser than medium-gravel, a pebble count, in which at least 100 bed-material particles are manually collected from the streambed and measured, is used to measure surface particle size (Wolman 1954). At each sample point along a cross section, a particle is retrieved from the bed, and the intermediate axis (not the longest or shortest axis) is measured. The measurements are tabulated as to number of particles occurring within predetermined size intervals, and the percentage of the total number in each interval is then determined. Again, the percentage in each interval is accumulated to give a particle-size distribution, and the particle-size data are reported as described above.

Wolman's method of pebble counts uses a sample of particles that is measured at cross sections of the channel bed or bar. A sieve analysis simply involves filtering a sediment sample through various sieves to characterize the range of particle sizes. The Wolman pebble count relies on measurements from a sample of surface sediments. To create a representative sample, the median diameter of each particle touched by the toe of one foot is measured at every step or series of steps in several passes across the channel. A sample size of at least 100 particles is usually necessary to conduct simple statistical analyses. With this method, a frequency distribution is usually created to identify the mean or median diameter and the diameter at two standard deviations from the mean. Several cross sections should be evaluated in a reach to determine the general character of the streambed. In addition to an analysis of channel geometry, a quantitative analysis of channel substrate particle size is conducted. Pebble counts (Wolman 1954) are conducted to determine bed material particle-size distribution in reaches that can be waded. At the three surveyed cross sections, a pebble-count transect is established, and the pebble count is conducted in the following method:

(1) Begin the count at each transect at bank-full elevation on the left bank and proceed to bank-full elevation on the right bank.

(2) Proceed one step at a time, with each step constituting a sampling point.

(3) At each step, reach down to the tip of your boot and, with your finger extended, pick up the first pebble-size particle touched by the extended finger.

(4) To reduce sampling bias, look across and not down at the channel bottom

when taking steps or retrieving bed material.

(5) As each particle is retrieved, measure the intermediate axis. If the intermediate axis cannot be determined easily, measure the long diameter and the short diameter of the particle, and determine the average of the two numbers.

Figure 3. Researchers on the left performing a Wolman Pebble Count using a gravelometer and sampling grid.

Subsurface and Bank Grain Size Distribution

For streams with no significant channel armor and bed material finer than medium gravel, bed material samplers developed by the Federal Interagency Sedimentation Project (FISP) (FISP 1986) may be used to obtain a representative sample of the streambed, which is then passed through a set of standard sieves to determine percent-by-weight of particles of various sizes. The cumulative percent of material finer than a given size may then be determined.

Sieving can be accomplished in the laboratory or field, using either wet or dry sieving procedures. The basic principle of this technique is as follows. A sample of known weight is passed through a set of sieves of known mesh sizes. The sieves are arranged in downward decreasing mesh diameters. The sieves are washed and shaken (field) or mechanically vibrated (laboratory) for a fixed period of time. The weight of sediment retained on each sieve is measured and converted into a percentage of the total sediment sample. This method is quick and sufficiently accurate for most purposes.

Sieving is difficult or ineffective for sieves finer that 200 mesh (200 screen wires/inch, or 75-µ openings). For silts and clays, the grain size should be determined by submitting a sample to a laboratory for analysis by settling in a water-filled tube (hydrometer analysis).

Sample Location

The locations at which bed or bank material sediment samples are collected depend upon the nature of the problem being investigated. Concerns associated with the deposition of fine sediments in pools of a stream, for example, necessitate the collection of sediment samples from these locations, and samples will primarily be taken from the surface of the bed. Thus, the sampling strategy and sample locations should reflect both an understanding of the underlying conditions and processes on the system of interest, and should constitute the minimum sampling effort needed to effectively support later analyses.

For most stream restoration projects, it is necessary to characterize the size of the sediments on the bed surface in order to compute resistance and stability. These samples are almost always collected from riffle or crossing sections, and usually consist of a series of representative samples that are then averaged. It is better to determine the average from several discrete samples analyzed separately rather than from several samples that are aggregated, then analyzed.

Recent studies have suggested that the size of sediments found on the surface of point bars at approximately their mid-point have a similar grain size distribution to the bed material load as determined from sampling of transported sediments. This approach holds promise but, as yet, has not been tested under a sufficient range of circumstances to warrant acceptance as an alternative to traditional approaches.

Sediment concentration in a natural stream varies from the water surface to the streambed and laterally across the stream, and can vary significantly with time, even at a fixed discharge. Concentration generally increases from a minimum at the water surface to a maximum at or near the streambed. Likewise, sediment sizes vary across the bed and in the banks. This variability should be considered when formulating the sampling strategy.

Resistance Estimates

For systems with gravel and coarser substrates, the sediment size has a significant influence upon overall energy loss through flow resistance. In finer grained streams, this influence is generally minor except that bed forms in sand bed streams often have a considerable effect upon resistance as well. A technical note in this series (in preparation), “Estimating Hydraulic Resistance for Stream Restoration Projects,” provides guidance for estimating resistance coefficients in various situations. A few of the common analytical procedures related to sediment size are summarized herein.

In the United States, it is customary to express flow resistance in terms of the coefficient n from Manning's Monomial Equation. Manning’s equation for mean velocity V (in feet per second or meters per second), is:

$$V = \frac{k_n}{n} R^{2/3} S^{1/2} \qquad (3)$$

where:
n = Manning’s roughness coefficient
R = hydraulic radius (Area/wetted perimeter)
k_n = 1 (SI units)
k_n = 1.486 (ft-lb-sec units)
S = energy, momentum, or water surface slope (depending on conditions)

Various means of estimating “n” have been proposed, including several empirical approaches that relate the depth of the flow to the size of sediments on the streambed.

Limerinos developed an empirical relative roughness equation for gravel bed streams using field data (Limerinos 1970). He correlated n-values with hydraulic radius and bed sediment size.

$$n = \frac{0.0925 R^{1/6}}{1.16 + 2.0 \log_{10}\left(\frac{R}{d_{84}}\right)} \qquad (4)$$

where
d_{84} = particle size for which 84 percent of the sediment mixture is finer
n = Manning's n value
R = Hydraulic radius

Limerinos's equation is not applicable to lower regime flow nor does it apply to situations where the sediment size is outside the range of 2–12 in., or where the depth of flow exceeds the sediment size by a factor of 10.

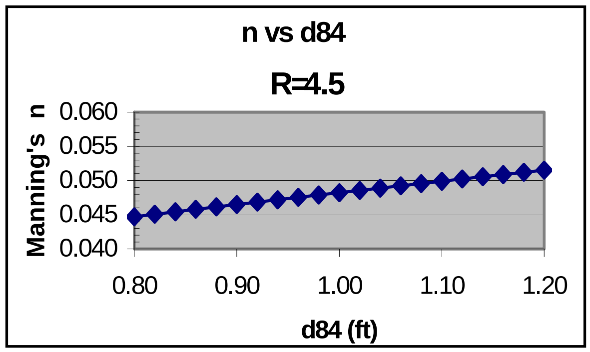

Figure 4. Variation of Manning’s n value with sediment size using Limerinos’ Equation – Moose River, NH.

Brownlie (1983) collected 77 sediment data samples containing 7027 data points. He used these data to formulate resistance relations on the basis of the mean sediment size, with separate equations for lower and upper regime flow conditions:

Lower Regime Flow:

$$n = \left(1.6940 \left(\frac{R}{d_{50}}\right)^{0.1374} S^{0.1112} \sigma^{0.1605}\right) \frac{d_{50}^{0.167}}{29.3} \qquad (5)$$

Upper Regime Flow:

$$n = \left(1.0213\left(\frac{R}{d_{50}}\right)^{0.0662} S^{0.0395}\sigma^{0.1282}\right)\frac{d_{50}^{0.167}}{29.3} \qquad (6)$$

where
d_{50} = median particle size of the sediment mixture
R = hydraulic radius of the stream
S = energy slope, water surface slope, or bed slope, in order of preference
σ = geometric standard deviation of the sediment mixture where:

$$\sigma = 0.5\left(\frac{d_{84}}{d_{50}} + \frac{d_{50}}{d_{16}}\right) \qquad (7)$$

If the slope is greater than 0.006, flow is always upper regime. Otherwise, the transition is correlated with the grain Froude number as follows:

$$F_g = \frac{V}{\sqrt{(s_g - 1)gd_{50}}} \qquad (8)$$

$$F_g' = \frac{1.74}{S^{1/3}} \qquad (9)$$

if $F_g \leq F'_g$ the flow is lower regime
if $F_g > F'_g$ the flow is upper regime

where
F_g = grain Froude number
s_g = specific gravity of sediments
V = velocity of flow
S = bed shape

Several other relations have been proposed including the Manning-Strickler equation advocated by the Federal Highway Administration (1975):

$$n = 0.04 * (d_{50})^{1/6} \qquad (10)$$

and the Bray (1979) relation:

$$n = 0.0593 * (d_{50})^{1/6} \qquad (11)$$

In the above relations, the sediment size is in meters. As with all empirical relations, the use of Equations 4 through 11 should not be extended beyond the constraints of their original data sets.

SYSTEM STABILITY ANALYSES

A number of factors can be considered in a system stability assessment. These include identifying the various types of sources (e.g., point, nonpoint, background), the relative location and magnitude of loads from the sources, the transport mechanisms of concern (e.g., runoff vs. mass wasting), the routing of the sediment through the stream or system, and the time scale of loading to the stream (i.e., duration and frequency of sediment loading). Of particular concern is identifying which processes impair the stream.

System stability evaluations are typically performed using a variety of tools, including existing monitoring information (field notes, local, measurements, permanent monitoring stations, and/or general observations), aerial photography analysis, simple calculations, stream gage and U.S. Geological Survey (USGS) data, spreadsheet analysis using empirical methods, and a range of computer models. The appropriate method is selected based upon the complexity of the problem, the availability of resources, time constraints, the availability of monitoring data, and the management objectives under consideration. The preferred method is one that addresses the questions at hand, uses existing monitoring information, and is consistent with the available resources and time constraints.

Sediment Yield

The purpose of a sediment yield analysis is to characterize the types, magnitudes, and locations of sources of sediment loading to the water body. Sediment yield is the amount of sediment passing a specified channel location, which may be substantially less than the amount actually eroded in the basin. Sediment yield is typically expressed as the total sediment volume delivered to a specified location in the basin, divided by the effective drainage area above that location for a specified period of time. Yield typically has the units of cubic meters/square kilometer/year or acre-ft/square mile/year. However, it is also sometimes necessary to estimate yield from a watershed from individual storm events of specified frequency (e.g., 2-, 10-, or 100-year events). Individual event yields are reported as cubic meters or tons per event.

Spatial and temporal variations in physical and biological features of the watershed make estimation of sediment yield an extremely difficult and imprecise task. Important variables include soils and geology, relief, climate, vegetation, soil moisture, precipitation, drainage density, channel morphology, and human influences. Dominant processes within a watershed may be entirely different between physiographic or ecological provinces, and may change with time. The problem becomes even more complex when grain size distributions and sediment yield for particular events must be estimated for input to sedimentation transport simulation models. There is no widely accepted procedure for computing basin sediment yield and grain size distribution directly from watershed characteristics without measured information.

Figure 5. Assessments of the stability of a stream and its watershed are necessary to identify causal mechanisms of impairment and to determine trends that must be considered in formulating remedial strategies.

Sediment deposition occurs in locations where energy for transport is insufficient to carry eroded sediments. Colluvial deposits, floodplain, and valley deposits, channel aggradation, lateral channel accretion, and lake and reservoir deposits are examples of typical geomorphic deposition processes. The stability and longevity of sediment deposits vary. Lake and reservoir deposits tend to be long-term, whereas some channel and floodplain deposits may be remobilized by the next large-scale flood event, only to be deposited downstream. The spatial and temporal variability of sediment production, transport and deposition greatly complicates the task of estimating sediment yield from a watershed.

Major factors and processes controlling sediment yield from watersheds should be described and discussed in the context of spatial scale, or size of watershed area. Area is an important predictor variable that usually is correlated with sediment yield. Sediment yield on very small areas is controlled by soil detachment, and as watershed size increases, sediment transport and deposition processes control sediment yield. Sediment yield from larger watersheds is controlled by sediment transport capacity of the channels that drain the watershed.

Bank Erosion Mechanisms

Erosion occurs when the hydraulic forces in the flow exceed the resisting forces of the channel boundary. The amount of erosion is a function of the relative magnitude of these forces and the time over which they are applied. The interaction of flow with the boundary of open channels is only imperfectly understood. Adequate analytical expressions describing this interaction have not yet been developed for conditions associated with natural channels. Thus, means of characterizing erosion potential must rely heavily upon empiricism.

The most common approaches to assessing the rate of erosion are 1) to compare sequential aerial photographs or existing channel cross-section surveys to determine the amount of bankline retreat over a period of time, and 2) to monitor changes at specific points by repetitive surveys or through the installation of bank pins. The first approach offers the benefit of providing immediate results for average bankline retreat, while the second method provides insight into event-specific bank loss.

Because erosion tends to be episodic, periods of 10 years or greater are recommended for either assessment method. The average rate of bankline retreat per year is computed, and can be multiplied by the average bank height and length to determine sediment yield from this source. Additional analyses may involve separating this load into the bed material and wash components based upon gradation analyses of the bank materials.

Erosion analyses also frequently include an assessment of the causal mechanisms of the "erosion," which is often only indirectly related to the force of moving water. Streambanks fail in one of four ways:

- Hydraulic forces remove erodible bed or bank material.
- Geotechnical instabilities result in bank failures.
- Mechanical actions cause a reduction in the strength of the bank.
- A combination of the above factors causes failure.

These modes of failure have distinct characteristics, and an investigation must be conducted to determine the specific mode of failure because this is often indicative of the underlying problem at a site or in a reach or system. Technical Note EMRRP SR-40 (in preparation) presents details on the identification and assessment of streambank erosion and failure.

Bed Level Changes

Sediment transport and deposition is simply the process of taking soil from one place and depositing it in another. Over time, these processes tend to balance themselves, with the predominant change being that of erosion in the headwaters region of a system, deposition in the lowlands, and no net change in the intermediate zones. Where significant changes occur in the bed level of a stream over a period of a decade or less, systemic instabilities are indicated.

Bed level changes are generally determined by comparing historic cross sections, but can also be determined by developing a specific gage analysis at a USGS gaging station, from interviews of residents, and from field observations such as the condition of bridge abutments, differences in bank-full indicator heights (abandoned floodplain levels), the elevation of indicator riparian vegetation species, or bank failure mechanisms.

Decreasing levels of bed elevation over time are generally indicative of (1) an increase in runoff from a watershed, (2) a decrease in sediment yield, or (3) previous channelization of downstream reaches. Increasing bed levels often suggest (1) an increase in sediment yield, (2) decreased bank stability associated with vegetation clearing, or (3) an increase in downstream water surface elevation associated with a dam or other obstruction.

Figure 6. Changes in bed levels can indicate systemic instabilities.

REACH STABILITY ANALYSES

The stability of a stream refers to how it accommodates itself to the inflowing water and sediment load. When the ability of the stream to transport sediment exceeds the availability of sediments within the incoming flow, and stability thresholds for the material forming the boundary of the channel are exceeded, erosion occurs. This technical note deals with the latter case of instability and distinguishes the presence or absence of erosion (threshold condition) from the magnitude of erosion (volume).

Incipient Motion (Threshold Condition)

As the flow over the bed and banks of a stream increases, a condition referred to as the threshold state is reached when the forces tending to move materials on the channel boundary are in balance with those resisting motion. The forces acting on a non-cohesive soil particle lying on the bed of a flowing stream include hydrodynamic lift, hydrodynamic drag, submerged weight (F_w – F_b), and a resisting force F_r. as seen in Figure 1. The drag is in the direction of the flow and the lift and weight are normal to the flow. The resisting force depends on the geometry of the particles (shape, protrusion, distribution, and shading effects). At the threshold of movement, the resultant of the forces in each direction is zero. Two approaches for defining the threshold state are discussed herein, initial movement being specified in terms of either a critical velocity (v_{cr}) or a critical shear stress (τ_{cr}).

Approaches for characterizing erosion potential can be placed in one of two categories: maximum permissible velocity, and tractive force (or critical shear stress). The former is advantageous in that velocity can be measured. Shear stress cannot be directly measured – it must be computed from other flow parameters. But shear stress is a better measure than velocity of the fluid force on the channel boundary. Moreover, conventional guidelines, including ASTM standards, rely upon shear stress as a measure for assessing the stability of erosion control materials.

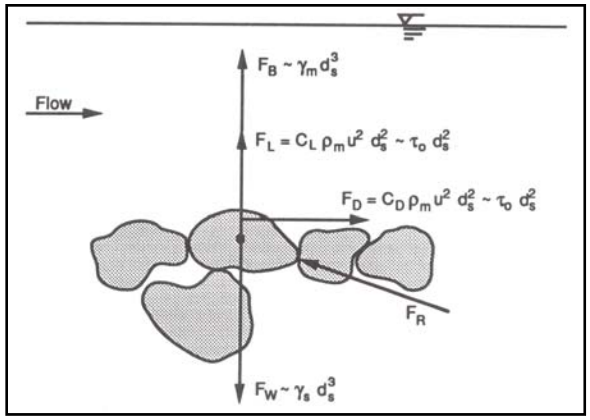

Figure 7. Forces acting on the boundary of a channel (adapted from Julien, 1995).

Critical Velocity

Figure 7 shows that both the lift and the drag force are directly related to the velocity squared. Thus, small changes in the velocity could result in large changes in these forces. The permissible velocity is defined as the maximum velocity of the channel that will not cause erosion of the channel boundary. It is often called the critical velocity because it refers to the condition for the initiation of motion. Early works in canal design and in evaluating the stability of waterways relied upon this method. Considerable empirical data exist relating maximum velocities to various soil and vegetation conditions.

However, this simple method for design does not consider the channel shape or flow depth. At the same mean velocity, channels of different shapes or depths may have quite different forces acting on the boundaries. The critical velocity is depth dependent, and a correction factor for depth must be applied. Despite these limitations, maximum permissible velocity can be a useful tool in evaluating the stability of various waterways. It is most frequently applied as a cursory analysis when screening alternatives.

Critical Shear Stress

The forces shown in Figure 7 can also be expressed in terms of the shear stress. The shear stress is the force per unit area in the flow direction. Its distribution in steady, uniform, two-dimensional flow in the channel can be reasonably described. An estimate of the average boundary shear stress (τ_o) exerted by the fluid on the bed is:

$$\tau_o = \gamma D S_f \qquad (11)$$

where γ is the specific weight of water, D is the flow depth (~ hydraulic radius), and S_f is the friction slope. Derived from consideration of the conservation of linear momentum, this quantity is a spatial average and may not provide a good estimate of bed shear at a point.

The critical shear stress (τ_{cr}) can be defined by equating the applied forces to the resisting forces. Shields (1936) determined the threshold condition by measuring sediment transport for values of shear at least twice the critical value and then extrapolating to the point vanishing sediment transport. His laboratory experiments have since served as a basis for defining critical shear stress. For soil grains of diameter d and angle of repose ϕ on a flat bed, the following relations can approximate the critical shear for various sizes of sediment.

For clays:

$$\tau_{cr} = 0.5\left(\lambda_s - \lambda_w\right) d \tan\phi \qquad (12)$$

For silts and sands:

$$\tau_{cr} = 0.25 d_*^{-0.6}\left(\lambda_s - \lambda_w\right) d \tan\varphi \qquad (13)$$

For gravels and cobbles:

$$\tau_{cr} = 0.06\left(\lambda_s - \lambda_w\right) d \tan\varphi \qquad (14)$$

where

$$d_* = d\left[\frac{(G-1)g}{\nu^2}\right]^{1/3} \qquad (15)$$

γ_s = unit weight of the sediment
γ_w = unit weight of the water/sediment mixture
G = specific gravity of the sediment
G = gravitational acceleration
ν = kinematic viscosity of the water/sediment mixture

The angle of repose ϕ for non-cohesive sediments is presented in Table 3 (Julien 1995), as are values for critical shear stress. The critical condition can be defined in terms of shear velocity rather than shear stress (note that shear velocity and channel velocity are different). Table 3 also provides limiting shear velocity as a function of sediment size. The V_{*c} term is the critical shear velocity and is equal to

$$V_{*c} = \sqrt{g R_h S_f} \qquad (16)$$

Table 3 provides limits best applied when evaluating idealized conditions, or the stability of sediments in the bed. Mixtures of sediments tend to behave differently from uniform sediments. Within a mixture, coarse sediments are generally entrained at lower shear stress values than presented in Table 3. Conversely, larger shear stresses than those presented in the table are required to entrain finer sediments within a mixture.

Table 3. Limiting shear stress and velocity for uniform non-cohesive sediments.					
Class name	**d_s (in)**	**ϕ (deg)**	**τ_{*c}**	**τ_{cr} (lb/sf)**	**V_{*c} (ft/s)**
Boulder					
Very large	>80	42	0.054	37.4	4.36
Large	>40	42	0.054	18.7	3.08
Medium	>20	42	0.054	9.3	2.20
Small	>10	42	0.054	4.7	1.54
Cobble					
Large	>5	42	0.054	2.3	1.08
Small	>2.5	41	0.052	1.1	0.75
Gravel					
Very coarse	>1.3	40	0.050	0.54	0.52
Coarse	>0.6	38	0.047	0.25	0.36
Medium	>0.3	36	0.044	0.12	0.24
Fine	>0.16	35	0.042	0.06	0.17
Very fine	>0.08	33	0.039	0.03	0.12
Sands					
Very coarse	>0.04	32	0.029	0.01	0.070
Coarse	>0.02	31	0.033	0.006	0.055
Medium	>0.01	30	0.048	0.004	0.045
Fine	>0.005	30	0.072	0.003	0.040
Very fine	>0.003	30	0.109	0.002	0.035
Silts					
Coarse	>0.002	30	0.165	0.001	0.030
Medium	>0.001	30	0.25	0.001	0.025

Uncertainty and Variability

The values presented in Table 3 generally relate to average values of shear stress or velocity. Velocity and shear stress are neither uniform nor steady in natural channels. Short-term pulses in the flow can give rise to instantaneous velocities or stresses of two to three times the average; thus, erosion may occur at stresses much lower than predicted. Because the limits in Table 3 were developed empirically, they implicitly include some of this variability. However, natural channels typically exhibit much more variability than the flumes from which these data were developed.

Sediment load can also profoundly influence the ability of flow to erode underlying soils. Sediments in suspension have the effect of damping turbulence within the flow.

Turbulence is an important factor in entraining materials from the channel boundaries. Thus, velocity and shear stress thresholds are 1.5 to 3 times that presented in the table for flows carrying high sediment loads.

The computed values for velocity and shear stress may be adjusted to account for local variability and instantaneous values higher than mean. A number of procedures exist for this purpose. Empirical methods based upon channel form and irregularity are most commonly applied. Several references at the end of this paper present procedures to make these adjustments. Chang (1988) is a good example. For straight channels, the local maximum shear stress can be assumed from the following simple equation:

$$\tau_{max} = 1.5\,\tau \qquad (17)$$

for sinuous channels, the maximum shear stress should be determined as a function of the planform characteristics using Equation 18:

$$\tau_{max} = 2.65\,\tau\left(\frac{R_c}{W}\right)^{-0.5} \qquad (18)$$

where R_c is the radius of curvature and W is the top width of the channel. Equations 17 and 18 adjust for the spatial distribution of shear stress; however, temporal maximums in turbulent flows can be 10 – 20 percent higher, so an adjustment to account for instantaneous maximums should be added as well. A factor of 1.15 is usually applied.

Sediment Continuity

The continuity of sediments through the project reach should be considered for most stream restoration projects. Continuity analyses are essentially sediment budgets, where the income and outflow are represented by the upstream and downstream reaches, respectively, and the net difference is represented by a change in the project reach. The "currency" is the bed material load of the stream. Continuity may be quantified, or assessed by means of trends analyses.

Trends Analyses

Continuity analyses can be accomplished without measuring or computing the actual sediment load by simply comparing the relative sediment transport capacities of the upstream, project, and downstream reaches. While this approach can indicate the trend of a reach toward aggradation, stability, or degradation, it cannot indicate the degree to which each will occur.

The general approach consists of assessing the ability of each of the three reaches to transport sediments at one or more discharges (generally the bank-full discharge and perhaps one larger event). Although actual sediment transport functions can be used for this analysis, surrogates that are easier to compute suffice (e.g. stream power, shear, etc.).

If the transport capacity of the up- and downstream reaches are equivalent and are also equivalent to the project reach, the project reach can be assumed stable (provided the upstream and downstream reaches are stable and have similar substrates). If the project reach has a lower transport capacity than the upstream reach, aggradation is likely. Table 4 presents combinations of conditions and possible outcomes. In instances where deposition is indicated, the amount of deposition can be roughly computed using sediment rating curves or transport functions.

Table 4. Example outcomes of relative transport capacity analyses.

Upstream	Project	Downstream	Outcome in Project Reach	Needed Quantification
0	0	0	Stable	None
0	0	+	Stable or degrading	Downstream degradation
0	0	-	Aggrading	Project deposition
0	+	+	Stable or degrading	Project bed stability
0	+	0	Erosion	Project bed stability
0	+	-	Stable, aggrading or degrading	Downstream deposition and project bed stability
0	-	-	Aggrading	Project deposition
0	-	0	Deposition	Project deposition
0	-	+	Stable, aggrading or degrading	Downstream degradation and project deposition

Quantification

Computation of sediment transport capacity will allow a rough check to determine if deposition is likely to be a problem. Numerous sediment discharge formulas have been developed, and some of the most commonly used formulae are summarized below and in Table 5. Sediment transport relationships are heavily dependent on the data used in their development. The selection of an appropriate discharge formula is an important consideration when attempting to predict sediment discharge in streams. If more than one formula can be used, the rate of sediment discharge should be calculated using each formula. The formulas that best agree with available measured sediment discharges should be used to estimate the rate of sediment discharge during flow conditions when actual measurements are not available.

Ackers and White (1973) is a total load equation and was developed for single grain sizes predominantly in the sand range, but subsequent modifications made by Ackers (1993) and at WES have incorporated multiple grain size calculations and gravel sizes. This function may grossly overestimate for fine sand and smaller size fractions.

Brownlie (1981) is a total load, single grain size function used for estimating sand transport.

Colby (1964) is a version of Colby's single grain size function, which has been modified at WES for multiple grain size calculations. It is valid for sand transport in streams and small rivers. It's a total load equation and attempts to account for wash load effects.

Einstein (Bed-load) (1950) is a multiple grain size function used to calculate the bed-load discharge of sand and/or gravel bed streams.

Einstein (Total-load) (1968) is a function that extends the bed-load calculations to include suspended load by grain size classes and sums them to get the total load.

Laursen (Copeland) (Copeland and Thomas 1989) is a modification to Laursen's (1958) multiple grain size function for sands and silts, extending its range to larger gravel sizes.

Laursen (Madden) (Madden 1993) is a multiple grain size function modified by Madden for sand bed transport. It can be used for mixtures of sand and gravel.

Meyer-Peter and Muller (1948) is a multiple grain size function for gravel bed rivers. It is a bedload equation and is not valid when appreciable suspended load is present.

Parker (1990) is a version of Parker's multiple grain size function. It can be applied to poorly sorted gravel bed streams. Because it is a bedload equation, finer sizes, less than 2 mm, must be excluded from the specified surface size distribution and the gradation must be 100 percent defined, i.e., there must be a size for which 0 percent of the material is finer. The bed material sizes used must be representative of the coarse upper layer of the bed.

Proffitt and Sutherland (1983) is a multiple grain size function modification of the Ackers-White formula. It can be used on sand and/or gravel bed streams which do not have considerable amounts of suspended sediment transport.

Toffaleti (1968) is a multiple grain size function for large sand bed rivers. It is not valid for gravel transport. It is a total load equation and is one of the best for big, sand bed rivers.

Yang's functions (1973, 1984) are functions for the assessment of single grain sizes for sands (1973) and gravels (1984). Both are total load functions. These relations have been modified at WES for multiple grain size calculations in sand and gravel bed streams (less than 10 mm). Very good predictions are made for sand bed streams with this relation, but a discontinuity exists at the 2-mm size.

Table 5. Summary of data used to derive sediment transport functions.				
Function	**Sediment Size (mm)**	**Slope**	**Velocity (fps)**	**Depth (ft)**
Ackers-White (1973)[2]	0.04-0.07	0.00006-0.037	0.07-7.1	0.01-1.4
Brownlie (1981)[3]	0.086-1.4	0.00001-0.0018	1.2-7.9	0.35-57
Colby (1964)[1]	0.18-0.70	0.000031-0.010	0.70-8.0	0.20-57
Einstein (1950)[2]	0.78-29	0.000037-0.018	0.9-9.4	0.03-3.6
Laursen (Copeland) (1989)[3]	0.08-0.70	0.0000021-0.0018	0.068-7.8	0.67-54
Laursen (Madden) (1985)[1]	0.04-4.8	0.00001-0.1	0.85-7.7	0.25-54
Meyer-Peter and Muller (1948)[1]	0.4-29	0.0004-0.02	1.2-9.4	0.03-3.9
Parker (1990)[1]	18-28	0.0097-0.011	2.6-3.7	1.0-1.5
Profitt(Sutherland) (1983)[1]	2.90-12	0.003	2.00-3.4	0.35-0.84
Schoklitsch (1930)[2]	0.3-4.9	0.00012-0.055	0.8-4.5	0.037-0.74
Toffaleti (1968)[3]	0.095-076	0.000002-0.0011	0.7-7.8	
Yang Sand (1973)	0.15-1.7	0.000043-0.028	0.8-6.4	0.04-50
Yang Gravel (1984)	2.5-7.0	0.0012-0.029	1.4-5.1	0.08-0.72
1 - derived from river data 2 - derived from flume data 3 - derived from river and flume data (only river data shown)				

Local Scour

Total scour is composed of 1) general scour, 2) contraction scour, and 3) local scour. In general, the components are additive. EMRRP Technical Note SR-05 (Fischenich and Landers 2000) provides guidance on computing general and contraction scour. Field observations and empirical relations are applied to estimate local scour. Both approaches have high degrees of uncertainty.

Two simple relations for estimating local scour depths along structures follow. The first is modified from Laursen's (1980) approach for scour at a bridge abutment and the second is based upon Froehlich's (1988) equations for live-bed scour at bridge crossings. Guidance for computing local scour at the toe of a revetment is also given in EM 1110-2-1601 (USACE 1991).

The Modified Laursen equation is applicable where the scour depth is less than four times the flow depth and where the encroachment (length of the structure projected normal to the flow) is less than seven times the flow depth. The modified Froehlich equations were based upon 170 live-bed scour measurements primarily in sand-bed streams.

Modified Laursen:

$$\frac{y_s}{y_a} = 1.3\left(\frac{Wo}{y_a}\right)^{0.48} \qquad (19)$$

Modified Froehlich:

$$\frac{y_s}{y_a} = 2\left(\frac{\theta}{90}\right)^{0.13}\left(\frac{Wo}{y_a}\right)^{0.43} F_r^{\,0.61} + 1.0 \qquad (20)$$

where

y_s = scour depth (ft) below the water surface

y_a = depth of flow at the structure (ft)

W_o = length of structure projected normal to flow (ft)

θ = angle of embankment to flow (deg)

Fr = Froude number of flow upstream of abutment

The modified Laursen equation implicitly includes contraction scour. For this equation, contraction scour should not be added to obtain total scour at the structure or in the section. The modified Froehlich equation does not include contraction scour, but does include a safety factor (+1.0) that effectively accounts for contraction scour in most cases. Values computed from either method should be increased by $y_a/6$ for sand bed streams if dunes are the expected bed form.

Local scour depths can be determined by measuring the maximum depth of scour in the vicinity of existing structures, contractions, or debris jams. Care should be exercised when applying this approach, however, because the maximum scour depth is often obscured by subsequent sediment deposition.

Scour chains can be installed in the bed of a stream to monitor both scour and fill. These are metal chains anchored onto plates and buried vertically in the channel bed. When a flood scours away the bed material, the exposed chain falls flat, forming a bend. Subsequent filling reburies the chain. The amount of scour can then be determined by comparing the original length of chain buried to the length left below the bed, and the amount of fill determined by measuring the depth of sediment above the bend in the chain. While the use of a scour chain can provide important information, the time required to obtain useful information can be significant.

OTHER ANALYSES

In addition to the measures and analyses discussed above, which are needed on most restoration projects, the circumstances of a particular project may warrant any number of additional efforts. This section provides an overview of some that are often applied.

Sediment Character

The degree to which fine sediments surround coarse substrates on the surface of a streambed is referred to as embeddedness. Although the term and its measurement were initially developed to address habitat space for juvenile steelhead trout, embeddedness measures have been used to assess fish spawning and macroinvertebrate habitat, as well as substrate mobility. Embeddedness is used as a water quality indicator in some areas.

No publications provide a comprehensive description of embeddedness, and the sampling methodology is far from standardized. Technical Note EMRRP-SR-36 (Sylte and Fischenich 2002) is a compendium of embeddedness techniques, compiled from journal papers, agency reports, and the personal files of those involved in the development of the techniques and their application. The note documents the definitions and usage of the term “embeddedness,” describes the development of embeddedness, provides guidelines for the application of measurement techniques, and summarizes the existing literature.

Contaminants are often associated with fine sediments within a stream because of the electrical bonds that form between the two. Most heavy metals and inorganic pollutants are associated with the clay fraction of the sediments in a system. In addition, organic sediment particles may harbor organic pollutants, and harmful bacteria and pathogens.

In instances where contaminated sediments are suspected, additional sampling and laboratory procedures may be applied to determine the concentration and distribution of the contaminants. A number of publications provide guidelines for sampling and testing procedures.

System Stability

Watershed modeling - both hydrologic and sediment yield - can be useful tools where quantification of sediment delivery and determination of the relative contributions from various sources are important to formulating alternative actions.

Erosion process models that focus on upland areas can yield reasonable results for most analyses. They are appealing in many cases because they can be applied without having to do extensive field work. These models are probably most effective for source analyses where the models have been applied and calibrated in the past, where sediment fate and transport after delivery is a less critical issue, and where sedimentation is associated primarily with sheet and rill erosion from relatively low-sloped lands. Such models should be used with caution in cases where extreme watershed conditions predominate (e.g., very steep topography, landslide-dominated erosion, radically variable precipitation regimes).

Models that estimate erosion as a function of several key factors, including soil characteristics, topography, vegetation characteristics, and precipitation are often used to quantify sediment sources. Many available methods are based on the Revised Universal Soil Loss Equation (RUSLE) or one of its many variants as applied by many agencies for erosion estimation over the past decade (e.g., AGNPS, SWRRBQ). Other methods commonly apply particle detachment and washoff equations to estimate erosion (e.g., HSPF, CREAMS, ANSWERS). Erosion process models vary substantially in the sophistication and technical expertise necessary to ensure proper application. Table 6 (USEPA 2001) summarizes the basic differences in method sophistication.

Table 6. Comparison of sediment source models (USEPA 2001).

Model Type/Examples	Key Capabilities and Limitations
Simple Methods: EPA Screening Procedure USGS Regression Procedure RUSLE WEPP	• Aggregate large land areas (not RUSLE) • Large time steps, e.g., average annual (not RUSLE) • Estimation methods based on empirical relationships and expert judgment • Do not model delivery processes. • Generally reliable only for relative comparisons of sources, not load estimates • Limited data; no calibration requirements
Mid-Range Models: BASINS-NPSM AGNPS ANSWERS R1/R4 WATSED BOISED WRENSS SWAT	• Compromise between empirical and mechanistic models • Reliable for order of magnitude accuracy • Can interface with GIS framework • Moderate data and calibration requirements • Some capable of evaluating transport and/or control effectiveness
Detailed Models: HSPF SWMM SWRRBQ ANSWERS SWAT CREAMS	• Can delineate sources at fine parcel scales • Can evaluate short time sequences/individual storm effects • Generally use mechanistic representations of key watershed functions to estimate erosion • Estimates generally accurate within factor of 1 to 2 • Often work best in interface with GIS framework • Substantial data and calibration requirements • Usually capable of evaluating transport and/or possible control effectiveness

Bank pins and successive cross section surveys are often used to quantify sediment yield from streambank erosion. Unfortunately, bank loss tends to be episodic, so these analyses are valuable only if they provide years (usually more than 10) of data.

Reach Stability

Sediment sorting analyses are sometimes assessed to determine reach stability or to evaluate changing substrate character for habitat analyses. Sorting is the process of flowing water removing finer particles from a graded bed material, leaving a coarsened gradation behind. Armoring occurs when the sorting process leaves the larger grains (which are non-transportable under the given flow conditions) on the bed and these gradually create a surface armor layer markedly coarser than the substrate.

During a wide range of flows, the armor layer prevents entrainment of finer sediment particles found in the substrate. When the armor layer becomes unstable, a wide array of the particles found in the bed is immediately mobilized. It is easy to visualize that the armor layer effectively “hides” smaller particles in the flow, but the finer particles also make movement of the coarse fraction easier – giving rise to the notion of equal mobility.

For many gravel- or cobble-bed rivers, a unique relationship between the discharge (or stage) and the sediment transport rate does not always exist. For the same discharge the sediment transport may differ by an order of magnitude. This is partly due to the equal mobility effect described above, and partly to inconsistent sediment yield from the watershed and streambanks. Once mobilized, the coarse material may not be transported far or for long, but the finer substrate material may be moved significant distances and continues to be transported at lower stages. In other words, the beginning of sediment transport occurs at a much higher discharge (or stage) than the cessation of the transport.

Vegetation influences the stability of a reach in several ways, and additional analyses of vegetation influences are sometimes warranted. Vegetation can increase the flow resistance in a stream because water flowing over the vegetation elements exerts a drag on the flow. Techniques to assess resistance caused by vegetation are provided in EMRRP TN-SR-7 (Fischenich 2000) and EMRRP TN-SR-8 (Fischenich and Dudley 2000).

Because the roots of vegetation stabilize the soils along streambanks, vegetation also impacts reach stability by reducing erosion. In general, the stable width of a well-vegetated stream is about one-half that for a stream without the assessed bank strength attributed to vegetation roots. Width relations for streams with and without vegetation are presented in EMRRP TN-SR-43 (in preparation).

Sediment Load Sampling

Estimating sediment movement, soil loss, and system stability from measurements of sediment movement in streams is problematic for several reasons. The measurements are time-consuming and expensive; the accuracy of the measurements is likely to be poor; and even if there are good data, where the soil came from and when is not known. But it is sometimes necessary to collect samples in order to develop sediment rating curves for detailed analyses of long-term trends in system stability, to assess water quality, or to determine conditions under which large volumes of sediment are delivered to the stream system.

Specially designed sediment samplers are used to collect water/sediment samples that are analyzed for sediment quantity and sometimes quality. Total sediment movement is sometimes estimated by measuring the amount of deposition in reservoirs or lakes.

From a measurement perspective, the sediment load in a stream is comprised of the suspended load and the bedload. Estimating suspended load by sampling is relatively simple, but taking a representative bedload sample is difficult.

The simplest type of suspended sediment sample is a grab sample obtained by dipping a container into the stream, preferably at a point where it is well mixed. The sediment in a measured volume of water is filtered, dried, and weighed. This measures the concentration of sediment and, when combined with the rate of flow, gives the rate of sediment discharge. Grab samples such as this generally underestimate actual transport by 20-40 percent because sediment concentrations are greatest near the bed, where grab samples are difficult to obtain. Temporal changes in sediment concentration present another challenge.

To overcome these problems, FISP has developed a series of sampling devices designed to collect water/sediment samples at various points in the water column or at different times. Depth-integrated samplers allow for variations in sediment concentration by collecting a sample that is a combination of small sub-samples taken from different points in the water column. In operation, the sampler is moved from the surface down to the bed and back up to the surface while sampling continuously. Point-integrated samplers overcome the temporal problem by remaining at a fixed point in the stream and sampling continuously or intermittently during the time it takes for the bottle to fill.

Suspended sediment samplers will only sample to a point about 0.3 ft (9.1 cm) above the streambed. The sediment transported in the unsampled zone is generally regarded as bedload, although it also includes sediments transported in suspension.

The bedload portion of sediment discharge is primarily sampled using two styles of bedload samplers: the FISP-designed U.S. series, and the more commonly discussed Helley Smith series. Bed-load samples are usually taken by lowering a specially made sampler to the streambed. Resting there, the sampler traps the material moving along the bottom.

Automated sampling procedures have been developed to take advantage of newer measurement technologies, such as acoustic Doppler, to measure sediment concentrations and even track individual particle movement. These techniques greatly enhance sampling efficiency, but are not currently employed with any frequency.

APPLICABILITY AND LIMITATIONS

The techniques described in this technical note are generally applicable to projects where the primary objectives include the enhancement of instream habitat, grade stabilization, erosion control, and aesthetics.

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> Fischenich, J. C., and C. Little. 2007. *Sediment sampling and analysis for stream restoration projects.* EMRRP Technical Notes Collection. ERDC TN-EMRRP-SR-39. Vicksburg, MS: U.S. Army Engineer Research and Development Center. *www.wes.army.mil/el/emrrp.*

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